IRRADIATION CREEP AND SWELLING OF RUSSIAN FERRITIC-MARTENSITIC STEELS IRRADIATED TO VERY HIGH EXPOSURES IN THE BN-350 FAST REACTOR AT 305-335°C

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OBJECTIVE

The objective of this effort is to provide data on the dimensional stability and mechanical properties of ferritic/martensitic steels after high fluence irradiation at temperatures below that obtainable in Western reactors.

SUMMARY

Russian ferritic/martensitic (F/M) steels EP-450, EP-852 and EP-823 were irradiated in the BN-350 fast reactor in the form of gas-pressurized creep tubes. The first steel is used in Russia for hexagonal wrappers in fast reactors. The other steels were developed for compatibility with Pb-Bi coolants and serve to enhance our understanding of the general behavior of this class of steels.

In an earlier paper we published data on irradiation creep of EP-450 and EP-823 at temperatures between 390 and 520°C, with dpa levels ranging from 20 to 60 dpa. In the current paper new data on the irradiation creep and swelling of EP-450 and EP- 852 at temperatures between 305 and 335°C and doses ranging from 61 to 89 dpa are presented. Where comparisons are possible, it appears that these steels exhibit behavior that is very consistent with that of Western steels. Swelling is relatively low at high neutron exposure and confined to temperatures <420°C, but may be camouflaged somewhat by precipitation-related densification. These irradiation creep studies confirm that the creep compliance of F/M steels is about one-half that of austenitic steels.

PROGESS AND STATUS

Introduction

Ferritic/martensitic (F/M) steels are widely used as structural materials in various types of reactor facilities. The main advantages of F/M steels are their high resistance to void swelling, low irradiation creep rates and a relatively low radioactivation after neutron irradiation. At the same time, the well-known disadvantages of these steels are their low long-term creep strength at high temperatures and their inclination to low-temperature irradiation embrittlement.

Earlier measurements of irradiation creep and short-term mechanical properties were performed as part of the current effort for two Russian F/M steels designated EP-450 (12Cr-1.3Mo-2V-Nb-B) and EP-823 (11Cr-1Mo-1Si-Nb, V, W) [1]. They were irradiated in the BN-350 fast reactor to doses of 20-60 dpa and have demonstrated that at irradiation temperatures below ~500°C the irradiation creep rate in the steels is rather low and consistent with measurements made on various Western F/M steels over the same temperature range.

Some results of this earlier study are shown in Figure 1 and demonstrate that not all strains measured in creep tests arise from irradiation creep alone. Note that at the irradiation temperature of 520°C an apparent increase of irradiation creep modulus is observed due to the onset of thermal creep and concurrent loss of strength. Note also that the creep modulus B appears to increase as swelling begins at lower temperatures. The data are also interpreted to show negative precipitation-related strains that lower the apparent creep modulus when the irradiation creep component is relatively small.

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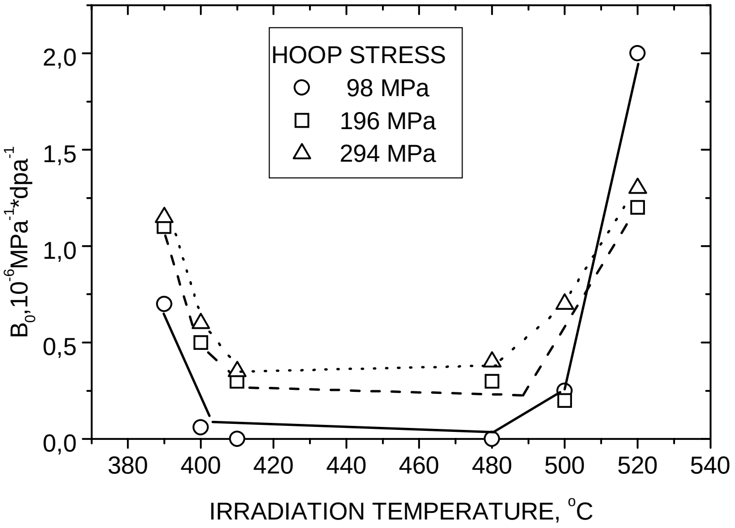

Figure 1. Average creep coefficients (B) derived for EP-450 in the range 390-520°C for three levels of hoop stress [1]. The data are interpreted to show the combined influence of swelling at low temperature, thermally assisted creep at higher temperature and precipitate-related densification over the entire temperature range. Similar behavior was observed in EP-823 at 390 and 480°C.

However, the most sought-after data for such steels are those at relatively low temperatures. Acquisition of such data require that the irradiation be performed in a reactor with a relatively low inlet coolant temperature, such as found in the BN-350 fast reactor in Kazakhstan but not available in Western reactors. In the present paper results are presented of further investigation of irradiation creep and swelling in EP-450 and EP-852 ferritic-martensitic steels. These steels were irradiated as pressurized creep tube cladding in the reactor BN-350 at temperatures in the range of 305-335°C to a maximum dose of 89 dpa.

Experimental Details

The measured chemical composition and final heat treatment of the creep tubes made of the EP-450 and EP-852 F/M steels are shown in Table 1. Creep tubes of 6.9 mm external diameter and 0.4 mm wall thickness (Figure 2) were used. To produce hoop stresses in the range 0 - 250 MPa at irradiation temperatures of 305-335°C, the tubes were filled with argon of 99.998% purity through a needle valve located in the large blank end flange. Note that one unusual feature of Russian tube fabrication is the use of annealing of tubes via electrical resistance for only seconds as shown in Table 1.

To reach high damage doses, the creep tubes were irradiated in the BN-350 reactor in special experimental subassemblies having extractable containers. These subassemblies are similar to regular driver subassemblies of the BN-350 reactor, but with 31 central pins replaced by an extractable cylindrical container of 32 mm in diameter. In each container, perforated cylindrical canisters were placed at different heights (Figure 3), with each of the canisters containing seven gas-filled tubes (one tube with zero gas pressure and six gas pressurized tubes, two tubes for each of three nominal hoop stress levels). The canisters were 97 mm in length, 26 mm in outer diameter and with 0.3 mm wall thickness. The required irradiation temperature for the creep tubes was ensured due to heating the container by surrounding pins. The calculated irradiation temperatures and doses for each container depend on the location of the canister with respect to the reactor core midplane. After irradiation in four consecutive

Table 1. The chemical composition of the EP-450 and EP-852 F/M steels.

Steel	Content, wt.%										
	C	Si	Mn	S	P	Cr	Ni	Mo	Nb	V	B
EP-450	0.14	0.20	0.31	0.009	0.017	12.95	0.20	1.54	0.47	0.22	0.004
	Solution treated 1050°C, 1 s + aged 850°C, 5 s.										
EP-852	0.13	1.91	0.31	0.009	0.017	13.15	0.27	1.69	-	-	-
	Solution treated 1050°C, 1 h + aged 720°C, 1 h.										

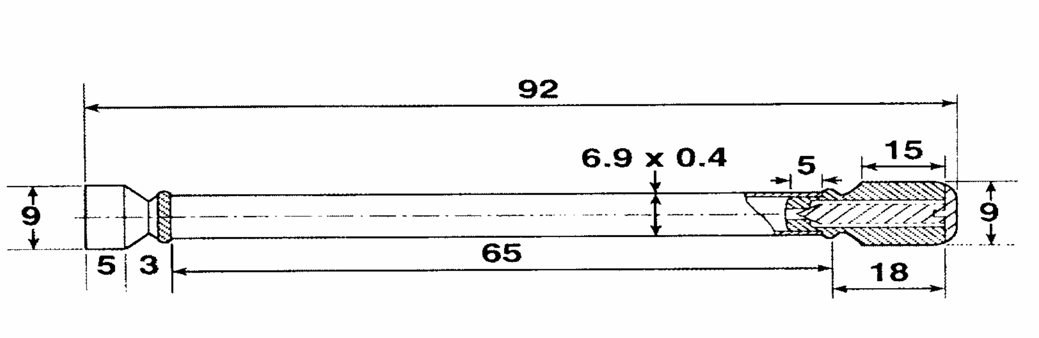

Figure 2. Irradiation creep tube (all sizes in mm.).

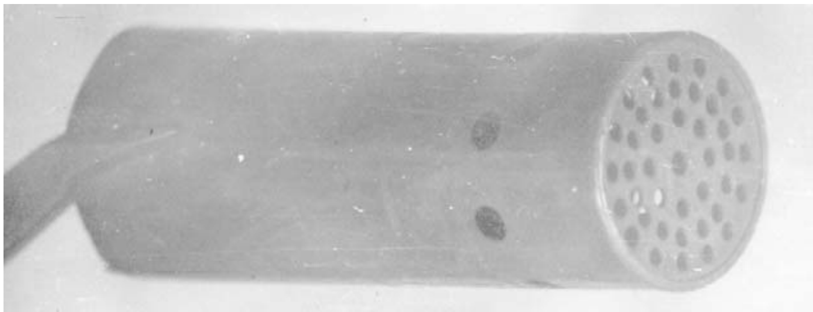

Figure 3. View of the canister for containing the creep tubes.

reactor runs the containers were extracted from the spent subassemblies and inserted in fresh subassemblies, which then were placed at the same positions in the core. Afterwards, the irradiation of the samples was continued for an additional four runs. The final calculated doses and irradiation temperatures for the steels investigated are shown in Tables 2 and 3.

The surfaces of the irradiated creep tubes were cleaned in 50% ethanol-water solution, and then the tube diameters were measured by a micrometer with an accuracy of 0.01 mm. For each tube the measurements were made at three cross sections: in the middle and at 15 mm apart from both tube ends, for two tube orientations that differ by rotation around the tube axis by 90°.

There were some gradients in dose and temperature along the tubes. For steels EP-852 (305°C/69 dpa), EP-450 (320°C/81 dpa) and EP-450 (335°C/89 dpa) the calculated gradient of dose was equal to 0.1 dpa/mm and the calculated gradient of temperature was 0.15°C/mm. For the distance of 50 mm between two cross sections at which tube diameters were measured, the difference of doses equals 5 dpa, and the difference of temperature was equal to 7.5°C. For EP-852 (310°C/61 dpa) and EP-450 (310°C/61 dpa) steels the calculated gradients of damage dose and of temperature were equal to 0.12 dpa/mm and 0.2°C/mm, respectively, so the doses and the temperatures vary by 6 dpa and 10°C, respectively.

For testing to ensure that the tube did not release its fill gas and for determining the actual hoop stresses, the tubes were punctured at room temperature in a remote installation of known volume and the pressure of the gas in that volume was measured. Hoop stresses at the end of irradiation were calculated from the following equation.

$$\sigma_\theta = P(T_0 / T)(V / V_0) d_{\mathrm{int}} / 2t \qquad (1)$$

where T is the temperature of the gas released from a punctured creep tube, P is the pressure of the released gas at temperature T, V is the volume of the puncture facility, T_o is the irradiation temperature, V_0 is the internal volume of the creep tube at temperature T_o, $d_{int.}$ is the internal tube diameter, and t is the tube wall thickness. The total irradiation creep strain ε^{ic} was determined as the difference between the total diametral strain and strain due to swelling (the diametral strain of the stress-free tube).

The irradiation creep modulus was calculated from the following equation, where the stress is the hoop stress.

$$B = \varepsilon^{ic} / 0.75\sigma_0 \times dpa \qquad (2)$$

Table 2. Irradiation creep characteristics of EP-450 F/M steel.

310°C/61 dpa				**320°C/81 dpa**				**335°C/89 dpa**			
σ_θ, MPa measured (nominal)	**Δd/d, %**	**ε^{ic}, %**	**B 10^{-6} (MPa×dpa)$^{-1}$**	**σ_θ, MPa measured (nominal)**	**Δd/d, %**	**ε^{ic}, %**	**B 10^{-6} (MPa×dpa)$^{-1}$**	**σ_θ, MPa measured (nominal)**	**Δd/d, %**	**ε^{ic}, %**	**B 10^{-6} (MPa×dpa)$^{-1}$**
0	0.1	0	0	0	0	0	0	0	0	0	0
59 (60)	0.3	0.2	0.74	49.8(50)	0.03	0.03	0.1	50.6(50)	0.19	0.19	0.56
59 (60)	0.3	0.2	0.74	50.1(50)	0.08	0.08	0.26	52.3(50)	0.25	0.25	0.72
0 (120)	0.1	0	0	94.6(100)	0.19	0.19	0.33	97.4(100)	0.45	0.45	0.69
69.5 (120)	0.6	0.5	1.57	94.4(100)	0.17	0.17	0.3	97.4(100)	0.40	0.40	0.61
130 (230)	1.1	1.0	1.68	190.8(200)	0.55	0.55	0.47	196.5(200)	0.97	0.97	0.74
141 (230)	1.2	1.1	1.7	190.5(200)	0.59	0.59	0.51	196.5(200)	0.97	0.97	0.74

Table 3. Irradiation creep characteristics of EP-852 F/M steel.

305°C/69 dpa					**310°C/61 dpa**				
σ_θ, MPa (nominal)	**σ_θ, MPa (measur.)**	**Δd/d, %**	**ε^{ic}, %**	**B, 10^{-6} (MPa×dpa)$^{-1}$**	**σ_θ, MPa (nominal)**	**σ_θ, MPa (measur.)**	**Δd/d, %**	**ε^{ic}, %**	**B, 10^{-6} (MPa×dpa)$^{-1}$**
0	0	0	0	0	0	0	0.1	0	0
50	38.5	0.05	0.05	0.25	60	56.0	0.15	0.05	0.19
50	38.2	0.03	0.03	0.15	60	58.0	0.3	0.2	0.75
100	100.5	0.1	0.1	0.19	120	0	0.35	0.25	-
100	99.5	0.1	0.1	0.19	120	77.0	0.45	0.35	0.99
200	143.8	0.25	0.25	0.33	230	0	0.45	0.35	-
200	143.0	0.25	0.25	0.33	230	35.0	0.35	0.25	1.56

Results

Upon removal of the tubes from the various canisters, a visual inspection of the creep tubes did not reveal any surface defects. All irradiated tubes retained their initial shape and appearance. As a result of mechanical loading, however, five creep tubes, namely, one tube of the EP-450 steel and four tubes of